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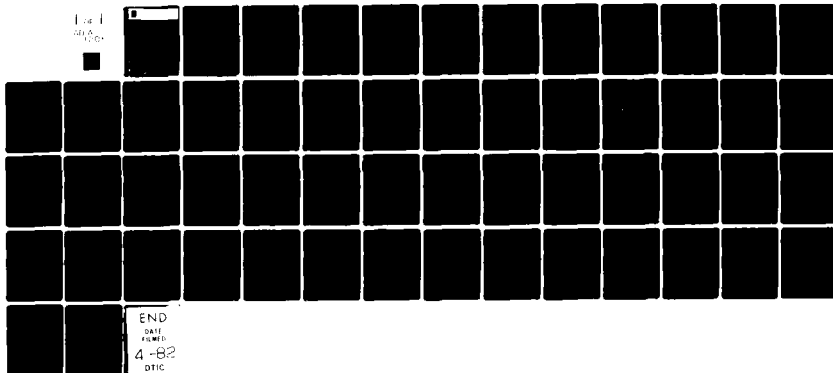
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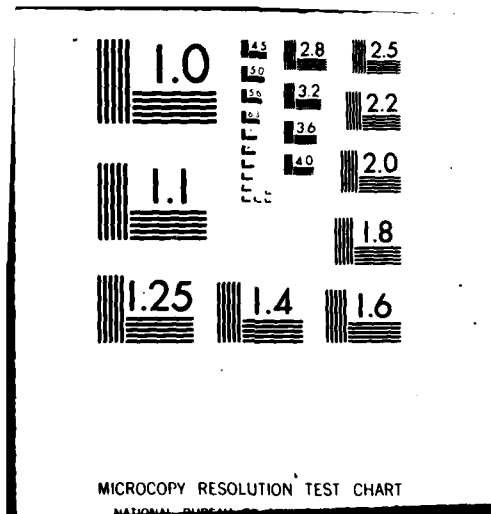
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Characterization of Environmentally Assisted Cracking for Design

State of the Art

National Materials Advisory Board
Commission on Sociotechnical Systems
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) High-strength structural alloys and weldments, such as those used in ship construction, can be exposed to deleterious environments under load and can experience environmentally assisted cracking (including stress-corrosion cracking and corrosion fatigue) during service. Designers cannot now anticipate with confidence a material's susceptibility to environmentally assisted cracking or determine how to characterize and incorporate such information in the design process (i.e., to quantitatively assess durability and reliability).		

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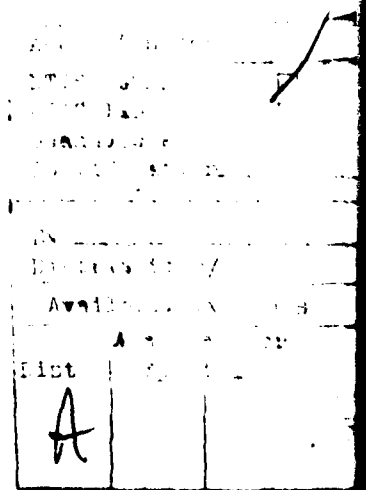
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20. (continued)

The committee affirmed the use of linear elastic fracture mechanics (LEFM) as a basis for materials characterization and design, and identified the relevant LEFM threshold and kinetic parameters for static loading conditions. The problems involved in the development of test methods for measuring cracking tendency and in the utilization of data in design are identified and discussed. The committee also expressed concern about the appropriateness of using static-load parameters in design for situations where minor or occasional load fluctuations (or changes) are known to occur. Based on the conclusions reached, a course of action that will advance the technology is recommended. It is further recommended that another panel be constituted to address the problem of environmentally assisted cracking under cyclically varying loads (i.e., corrosion fatigue).

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DEDICATION

This report is dedicated to the memory of B. Floyd Brown, a member of the committee who died just before its completion. The committee regrets his passing and that he was not able to see the end product of his and his colleagues' efforts.

ABSTRACT

High-strength structural alloys and weldments, such as those used in ship construction, can be exposed to deleterious environments under load and can experience environmentally assisted cracking (including stress-corrosion cracking and corrosion fatigue) during service. Designers cannot now anticipate with confidence a material's susceptibility to environmentally assisted cracking or determine how to characterize and incorporate such information in the design process (i.e., to quantitatively assess durability and reliability).

The committee affirmed the use of linear elastic fracture mechanics (LEFM) as a basis for materials characterization and design, and identified the relevant LEFM threshold and kinetic parameters for static loading conditions. The problems involved in the development of test methods for measuring cracking tendency and in the utilization of data in design are identified and discussed. The committee also expressed concern about the appropriateness of using static-load parameters in design for situations where minor or occasional load fluctuations (or changes) are known to occur. Based on the conclusions reached, a course of action that will advance the technology is recommended. It is further recommended that another panel be constituted to address the problem of environmentally assisted cracking under cyclically varying loads (i.e., corrosion fatigue).

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CONTENTS

	Page
Chapter 1 INTRODUCTION	1
Chapter 2 CONCLUSIONS AND RECOMMENDATIONS	5
Conclusions	5
Recommended Course of Action	6
Chapter 3 TECHNICAL BACKGROUND	9
The Problem	9
Approaches and Relevant Parameters	10
State of the Art of Design Methods	14
State of the Art of Test Methods	21
Chapter 4 VARIABLES THAT INFLUENCE ENVIRONMENTALLY ASSISTED CRACKING RESPONSE	27
Mechanical and Geometric Variables	27
Environmental Variables	31
Metallurgical Variables	33
Chapter 5 VARIABILITY AND PROBLEMS IN THE MEASUREMENT OF ENVIRONMENTALLY ASSISTED CRACKING RESPONSE	37
Variability	38
Testing Problems	39
Chapter 6 PROBLEMS AND NEEDS	41
Sustained-Load Cracking	41
Fatigue Cracking	43
Appendix CURRICULA VITAE OF COMMITTEE MEMBERS	45

LIST OF TABLES AND FIGURES

		Page
Table 1	Influence of Cut-Off Time on Apparent K_{ISCC} Using the Initiation Method	18
Table 2	Results of Long Time K_{ISCC} Tests Using the Arrest Method	18
Table 3	Assessment of K_{ISCC} by the Initiation and Arrest Methods	18
Figure 1	Recommended course of action	7
Figure 2	Test geometries used to characterize environmentally assisted cracking behavior	11
Figure 3	Schematic representation of time-to-failure under sustained loads	13
Figure 4	Schematic diagram of environmentally assisted crack growth behavior	15
Figure 5	Graphical presentation of small defect criterion	20
Figure 6	Effect of stress fluctuations on the threshold stress for precracked cantilever-beam specimens	29

Chapter 1

INTRODUCTION

At the request of the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA), the National Materials Advisory Board (NMAB) Committee on Environmentally Assisted Cracking Test Methods for High-Strength Steel Weldments was formed in May 1980 to provide advice concerning establishment of a meaningful and standardized test methodology for characterizing, in terms useful to structural designers, the environmentally assisted cracking characteristics of high-strength steel weldments. The broader goal of the committee was to examine the overall problem of environmentally assisted cracking of high-strength structural alloys and to determine what is needed to bring the state of the art for designing against environmentally assisted cracking to a level that is comparable to that for designing against fracture.

In addition to the chairman, an expert in fatigue and environmentally assisted cracking, the committee was selected to represent individuals knowledgeable in the following areas:

- o development of test methods
- o theoretical bases of stress corrosion cracking
- o corrosion
- o application of predictive methodology to engineering structures exposed to corrodents
- o relevant ASTM activities

Environmentally assisted cracking in structural alloys, incorporating both crack initiation and crack growth, has been recognized as an important cause of failure in engineering structures. These processes of initiation and growth can occur when a material is subjected to the conjoint actions of an applied (static or fluctuating) stress and a deleterious environment. These phenomena have been traditionally called stress-corrosion cracking (SCC) (including hydrogen embrittlement) and corrosion fatigue (CF). Stress-corrosion cracking is associated with a static or constant stress, and corrosion fatigue, with a fluctuating or cyclically varying stress. Other types of embrittlement, such as by

liquid metals, were considered beyond the scope assigned. At the same time, it was felt that to be of service, environmentally assisted cracking must be looked at broadly, and not restricted to test methodology alone.

In the past SCC and CF were believed to be governed by very different mechanisms (Brown 1972, Scully 1971 and Uhlig 1951) and were viewed as distinctly separate problems in engineering practice. More recent investigations, however, have shown that the same fundamental mechanisms, in some cases, can be responsible for both of these phenomena (Pao et al. 1979, Simmons et al. 1978, Wei 1979, Wei and Landes 1969, Williams et al. 1979, and Weir et al. 1980). Comprehensive discussions of the mechanisms and phenomenology of environmentally assisted cracking are given in the proceedings of several recent symposia (Devereux et al. 1971, Hochmann et al. 1973, Staehle et al. 1969). The use in this report of the more general term "environmentally assisted cracking" reflects this more recent thinking; nevertheless, only the case of environmentally assisted cracking under static stresses (i.e., stress corrosion cracking) is considered. The choice is a pragmatic one and is consistent with current engineering practice. It circumvents the need for addressing a host of issues relating to the influences of loading variables (e.g., frequency, waveform, load ratio, load sequence) on corrosion fatigue which will need to be considered separately. The influences of minor stress fluctuations about a steady-state stress and of infrequent changes in stress level (such as those associated with startup and shutdown) on cracking response, however, are considered. The magnitudes and nature of these stresses are such that they are not regarded in current engineering practice as being germane to fatigue even though they may lead to corrosion fatigue.

The traditional measure of SCC susceptibility is given in terms of the time required to produce failure (time-to-failure) at different stress levels or in terms of the so-called threshold stress level below which a part might be expected to survive indefinitely. These data are obtained from tests of "smooth" specimens of the material in the appropriate deleterious environments. The time-to-failure (which is used as the primary measure of cracking response in these tests), however, incorporates both the time required for crack initiation and a period of slow crack growth so that the separate effect of the environment on each of these processes cannot be ascertained. (A part of this difficulty stems from the lack of a precise definition for crack initiation.) Although both crack initiation and crack growth can influence significantly the serviceable lives of engineering structures, the current design emphasis on the considerations of cracked bodies (i.e., designs based on the presumption of pre-existing crack-like flaws in the structure) circumvents the problems of crack initiation. In concert with this design emphasis, this study addresses only those issues that directly relate to the crack-growth aspects of environmentally assisted cracking in high-strength alloys.

The committee's conclusions and recommendations are presented without elaboration in Chapter 2. A critical assessment of the problems associated with environmentally assisted cracking in high-strength alloys

and of the state of the art of design and test methodology as well as a discussion of relevant parameters are presented in Chapter 3. Variables that influence environmentally assisted cracking response are considered in Chapter 4, and sources of variability and testing problems are discussed in Chapter 5. Problems that relate to the characterization of environmentally assisted cracking of high-strength alloys and high-strength steel weldments are identified in Chapter 6.

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Chapter 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based on its study the NMAB Committee on Environmentally Assisted Cracking Test Methods for High-Strength Steel Weldments has concluded that:

1. Design against environmentally assisted cracking is much more complex than designing against fracture because of the chemistry-mechanics-metallurgy synergism and the consequent need to consider a range of environmental variables and their variations with time and interactions with the loading and metallurgical variables.
2. Fracture mechanics of cracked bodies is a valid and useful approach for designing against environmentally assisted cracking. There are, however, limitations and difficulties that must be taken into consideration.
3. For static loading, K_{Isc} and da/dt versus K_I are useful. They are specific to a material, a temperature, and an environment-material system and also are functions of local chemical composition, microstructure, etc.
4. In practice, K_{Isc} can be defined only as the K_I level associated with some acceptably and definably low rate of crack growth, which is commensurate with the design service life. Because of nonsteady-state crack growth and other factors, K_{Isc} obtained from increasing and decreasing K_I tests may be different, even though the difference may be small.
5. Superimposed minor load fluctuations and infrequent changes in load can alter environmental cracking response. This effect, which cannot be predicted from K_{Isc} and da/dt , may be significant and detrimental and requires the re-examination of static loading as a design premise.

6. Major fluctuations in load may lead to corrosion fatigue and must be addressed separately. Some believe that this is a more serious part of the problem of environmentally assisted cracking.

7. Existing test methodology for environmentally assisted cracking tendency is applicable to the evaluation of weldments. As in other structural materials, residual stress must be treated in a quantitative and realistic way.

RECOMMENDED COURSE OF ACTION

The following three-phase course of action (Figure 1) is recommended to resolve a number of the outstanding critical issues and to further advance the technology so that rational methods for materials characterization and for design against environmentally assisted cracking can be formalized.

Phase I--Test Rationale

The objective of phase I is to establish quantitatively the rational basis for measuring the static load parameters, K_{ISCC} and da/dt , and to assess the appropriateness of these parameters for design against environmentally assisted cracking. This phase will involve the following:

1. Examination of crack growth initiation and crack growth arrest (for increasing and decreasing K_I tests) as criteria for determining K_{ISCC} , particularly with respect to uniqueness of test results.
2. Investigation and quantification of test duration for proper assessment of K_{ISCC} in the relevant environment (role of incubation in testing and in life prediction).
3. Examination of the effect of load fluctuations on the static load parameters, K_{ISCC} and da/dt , and establishment of the appropriateness of these parameters to design and service.
4. Characterization of crack tip environment in relation to crack initiation and growth.

Phase II--Technology Development

Based on the outcome of phase I, the following studies may be redirected towards cyclic or fatigue load instead of static loads:

1. Weldments--Examination of the role of residual stresses and development of appropriate technology for their quantitative incorporation as a part of the crack driving force. Investigation and quantification of the influences of inhomogeneities in composition and microstructure on cracking response.

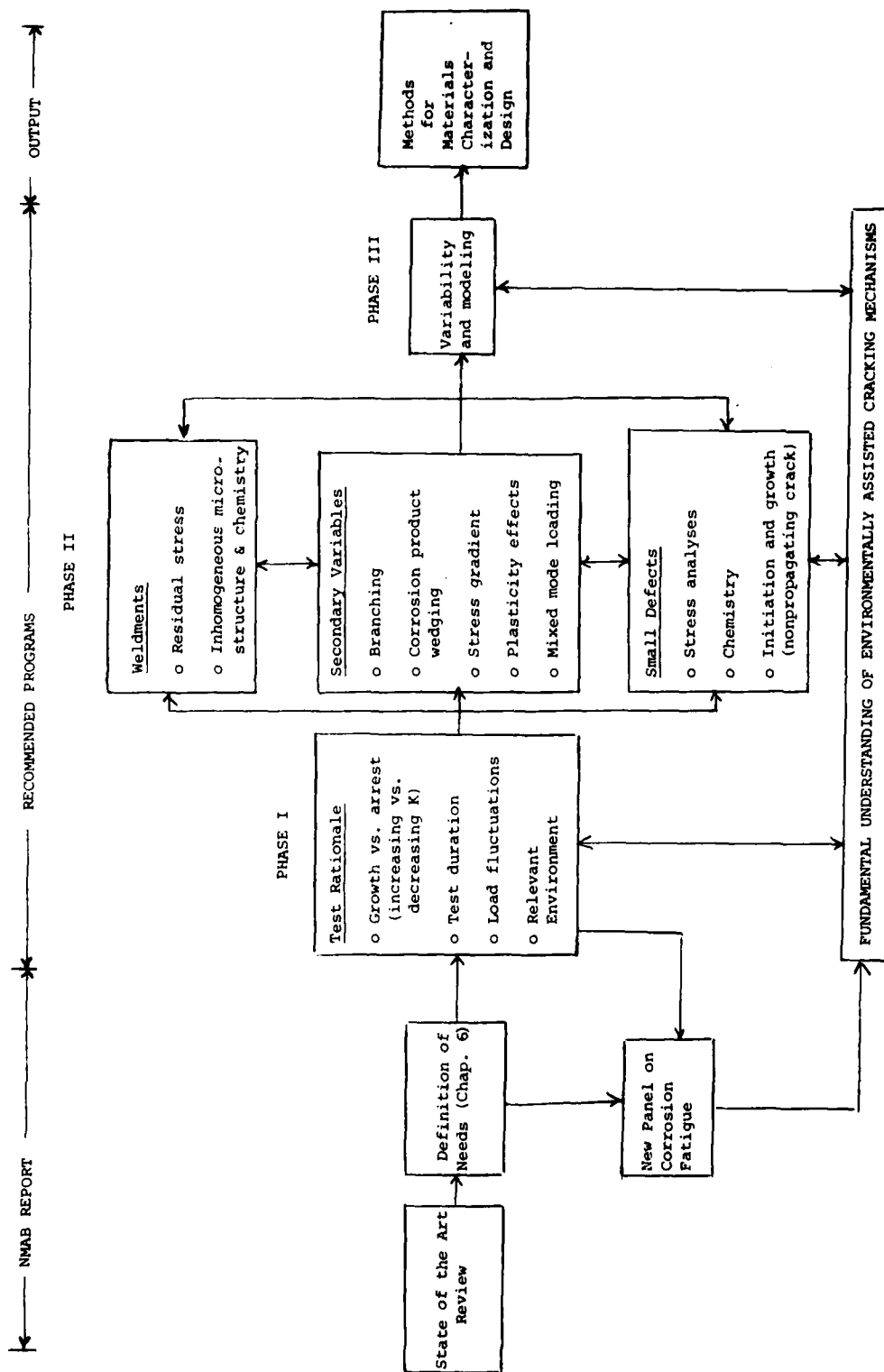


FIGURE 1 Recommended course of action.

2. Secondary Variables--Investigation and quantification of the effects of secondary variables with respect to materials characterization and design, particularly with respect to the influences of crack branching, corrosion product wedging, stress gradient, plasticity effects, and mixed mode loading.

3. Small Defect--Development of the technology for dealing with small defects, namely, those for which the applicability of continuum mechanics is questionable and the crack tip chemistry may be significantly altered from that of the bulk environment.

Phase III--Variability and Modeling

To quantify data for design, a methodology for dealing with variability and modeling of crack-growth response must be developed, on the basis of fundamental understanding, to permit reliable estimates of service performance at lifetimes that are one or more orders of magnitude longer than the materials characterization data.

It is essential that work in all of these phases (i.e., phases I, II, and III) be supported and guided by fundamental understanding of the mechanisms of environmentally assisted cracking. In addition, it is recommended that a separate committee (such as that of the National Materials Advisory Board) be constituted to address the problems of environmentally assisted fatigue growth (i.e., corrosion fatigue). Resolution of these problems is an essential part of the development of methodology for designing against environmentally assisted cracking of structural alloys, including weldments.

Chapter 3

TECHNICAL BACKGROUND

THE PROBLEM

The increasing use of high-strength structural materials in deleterious environments (e.g., sea water) requires a quantitative knowledge of the environmental effects on materials performance so that designers can predict the useful life of components. The influence of the environment on degradation of structural materials may manifest itself in the form of stress-corrosion cracking, hydrogen embrittlement, and corrosion fatigue--all of which may be broadly grouped under the heading of environmentally assisted cracking phenomena.

In the narrower context of this report, environmentally assisted crack growth or, more specifically, stress-corrosion cracking refers to that aspect of fracture behavior in which a static load and a deleterious environment combine synergistically to cause the development and growth of cracks in structural materials. Like other mechanisms for crack initiation and growth (e.g., creep and fatigue), this process is time dependent and can lead to catastrophic failure at stresses substantially lower than the conventional yield strength of the material.

Although long recognized as an important potential cause for failure, the basic underlying mechanisms for environmentally assisted cracking remain unresolved for the most part (Brown 1972, Devereux et al. 1971, Hochmann et al. 1977, Scully 1971, Staehle et al. 1969) and quantitative design procedures against its occurrence essentially do not exist. In addition, the field is plagued with confusion created to a large extent by: (1) The very complex multifaceted nature of the phenomenon which involves chemistry, mechanics, and metallurgy; (2) the extremely large number of variables that are known to affect or are suspected of affecting its behavior; (3) relatively poor correlations between laboratory test results and service experience; (4) extensive data scatter; and (5) the absence of standardized methods for quantitatively assessing a material's cracking susceptibility. Further complications arise from the fact that clear distinction is not always made between the crack-initiation (nucleation) and crack-growth phases despite evidence that shows the likelihood of a significant difference between the mechanisms and behaviors for these processes. In view of such difficulties, environmentally assisted cracking represents one of

the most complex areas of fracture behavior, and it is extremely difficult to design against this phenomenon and to make life predictions. The design difficulties are exacerbated by the large variety of tests that are being used currently to characterize environmentally assisted cracking behavior and by the potential for widely differing interpretations of the test results. Figure 2 illustrates some of these test procedures. The confusing state of affairs in designing against environmentally assisted cracking is further illustrated and underscored by the growing number of structural failures attributed to this phenomenon.

APPROACHES AND RELEVANT PARAMETERS

Approaches and Design Philosophies

There is no explicit design methodology for environmentally assisted cracking at this time. A number of design philosophies are used to guide materials selection and in "post design" analysis. Current approaches for structural design and for the selection of materials to prevent environmentally assisted cracking can be divided into two categories--those based on crack initiation and those based on crack growth. The primary difference between these design philosophies is the basic assumption regarding the initial condition of the hardware. For the case of crack initiation, it is assumed that the component is essentially free of crack-like defects at the start of life and the time to initiate a crack under the expected service conditions (environment and applied stresses) becomes the primary concern. The crack-growth philosophy, on the other hand, presumes the presence or early development of cracks or crack-like defects. Hence, crack growth under the expected service conditions becomes the primary concern.

The case of thin-walled seamless tubing with good surface finish serves as an example for the use of crack-initiation philosophy. Here the presence of crack-like surface defects may be ruled out, and crack initiation may be considered to be a life-limiting process. Test data obtained with smooth (i.e., uncracked) specimens exposed to specific deleterious environments can be used for design. When structural members (which frequently also include weldments) of considerable thickness are used, crack-like surface flaws are likely to be present and stable crack growth under the influence of the aggressive environment is likely to be life-limiting. Consequently, the crack-growth philosophy becomes more appropriate and pre-cracked specimens are used to obtain crack-growth data for design.

Ideally, design against environmentally assisted cracking should incorporate both the crack-initiation and crack-growth design philosophies. Unfortunately, however, because of the limitations of currently available nondestructive inspection techniques, it is not always reasonable to presume that a structure is free of defects (even though they may be very small). Consequently, a cracked-body assumption usually is adopted and the crack-growth rate then becomes the dominating

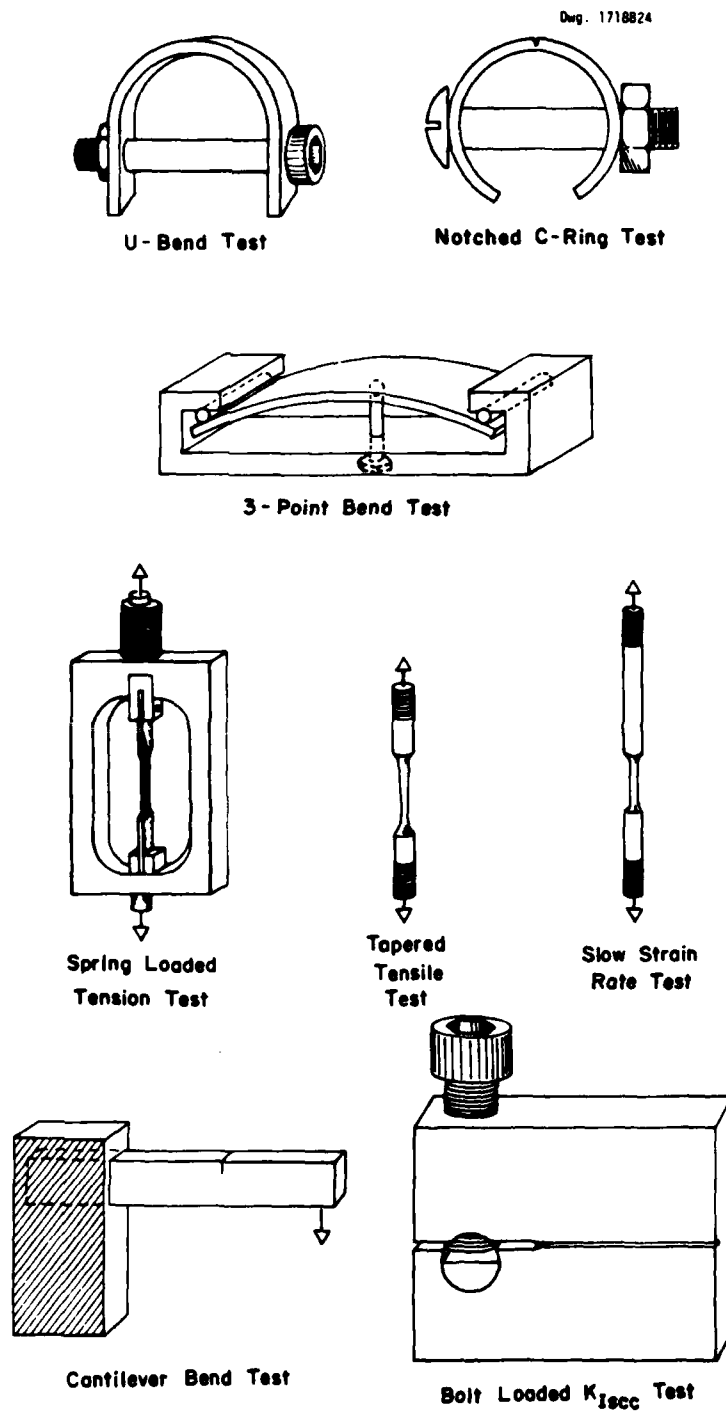


FIGURE 2 Test geometries used to characterize environmentally assisted cracking behavior.

factor for design. The applicability of the crack-initiation and crack-growth design philosophies to the prevention of environmentally assisted cracking depends on both the nature of the component involved and the capabilities of applicable nondestructive inspection procedures. For structures made of relatively heavy sections (e.g., high-strength steel weldments being considered here), it is nearly impossible to ensure that they are free of defects. Therefore, a crack-growth design philosophy appears to be the most defensible, and the remainder of the discussion is limited primarily to this design philosophy. Relevant parameters for characterizing the resistance of materials to environmentally assisted cracking are considered in this context.

Definition of Relevant Parameters

Extensive research on the fracture problem has led to the introduction of linear elastic fracture mechanics (LEFM) to the treatment of cracked-body problems (Irwin 1957, Paris and Sih 1965, and Sih 1973). The principle of LEFM is that the stress (strain) field ahead of the crack tip can be characterized by means of a single parameter, the stress intensity factor K , which is expressed in $\text{MPa}\sqrt{\text{m}}$. This parameter is related to the applied stress, the crack size and the geometry of the crack and of the component (Irwin 1957, Paris and Sih 1965, and Sih 1973), and is defined in terms of the three principal modes of loading (i.e., the tensile opening mode or mode I, the forward sliding mode or mode II, and the longitudinal shearing mode or mode III). It has been used successfully to characterize a material's resistance to fracture (unstable crack growth) in terms of the plane-strain fracture toughness, K_{IC} , and other toughness parameters, such as the R curves (American Society for Testing and Materials 1965, 1967, 1972 and 1979). The use of LEFM in materials characterization and design against fracture, for high-strength alloys, is well established.

Since crack growth and environmental attack would be expected to occur in the highly stressed region at the crack-tip, the stress (or strain) distribution in this region is of primary importance, and again K can be used to characterize the mechanical driving force (Johnson and Paris 1968, Wei 1969, Wei et al. 1972). K factors for many different loading conditions and body configurations and numerical solutions for K factors of practical test specimens have been well documented in the literature (Sih 1973 and The American Society for Testing and Materials 1965, 1967, and 1972). For environmentally assisted cracking, the stress intensity factor for the opening mode (mode I) of crack growth, K_I , generally is used, since this mode predominates (Johnson and Paris 1968, Wei 1969, Wei et al. 1972).

One approach to the characterization of environmentally assisted cracking under static loads has been to determine the threshold stress intensity (K_{th} or K_{Isc}) for a particular set of material-environment conditions, including temperature (Brown 1964, 1968). Conceptually, K_{th} or K_{Isc} represents a threshold value of K below which environmentally induced crack growth in pre-cracked specimens does not occur (Figure 3). K_{Isc} refers to the threshold value of K under

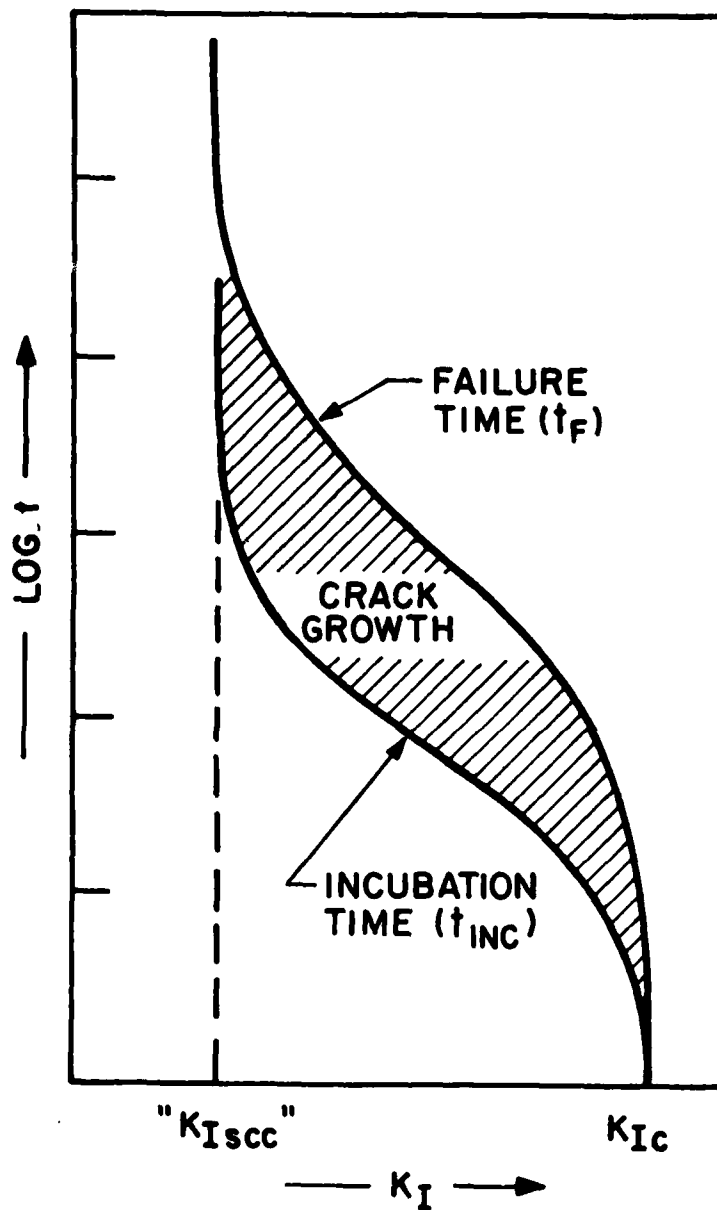


FIGURE 3 Schematic representation of time-to-failure under sustained loads (Wei et al. 1972).

plane-strain conditions (often for aqueous or stress corroding environments). K_{th} , on the other hand, is commonly used to indicate more relaxed conditions of constraint and for other environments (such as hydrogen). At K values above K_{ISCC} , stable crack growth occurs under the influence of the deleterious environment until the K_{IC} value is reached and crack growth becomes unstable.

Another parameter of significance is the rate of sustained-load crack growth, da/dt , as a function of K in a deleterious environment. Typical behavior is shown schematically in Figure 4, which represents a plot of the log of crack-growth rates versus K (Wei et al. 1972). From Figure 4 it is apparent that one can choose some low value of growth rate as a basis for defining K_{th} or K_{ISCC} . For the accurate determination of K_{ISCC} , considerable care in measuring crack growth and long testing times generally are required.

The determination of K_{ISCC} and da/dt under purely static loading conditions may not be adequate because actual service loads are rarely static. In most real situations, the loading on a given structure may consist of static loads with superimposed cyclic loads. It may be necessary, therefore, to consider corrosion fatigue as well. Useful parameters for characterizing corrosion fatigue include determinations of the rates of crack growth per cycle, da/dN , in deleterious media as a function of ΔK , K_{max} , and frequency (Barsom 1972, McEvily and Wei 1972, and Wei and Speidel 1972). The stress intensity range, ΔK , is defined simply as the difference between K_{max} and K_{min} , the maximum and minimum stress intensities encountered during each loading cycle (American Society for Testing and Materials 1981).

Because of the very complex interactions involved in environmentally assisted cracking under cyclically varying loads, detailed considerations of this problem are intentionally omitted from this report. As such, only those parameters associated with statically applied loads (i.e., K_{ISCC} and da/dt versus K_I) will be considered. Perturbations to these parameters caused by superimposed small amplitude load variations, however, will be discussed.

STATE OF THE ART OF DESIGN METHODS

The prevailing cracked-body design approach to prevent environmentally assisted cracking is based on the concepts of linear elastic fracture mechanics (Irwin 1957, Paris and Sih 1965). Specifically, LEFM provides a quantitative parameter, K_I , that can be used to describe the mechanical driving force for the onset of environmentally assisted cracking in the presence of a crack-like defect and for the subsequent crack growth. Typically, the fracture mechanics characterization of environmentally assisted cracking behavior involves the measurement of a threshold parameter, K_{ISCC} , which is intended to define the K_I level (combination of applied stress and flaw size) below which cracking will not occur, and of the crack growth rate, da/dt , as a function of K_I levels above the threshold. The K_{ISCC} and da/dt versus K_I data are specific to a given material-environment combination.

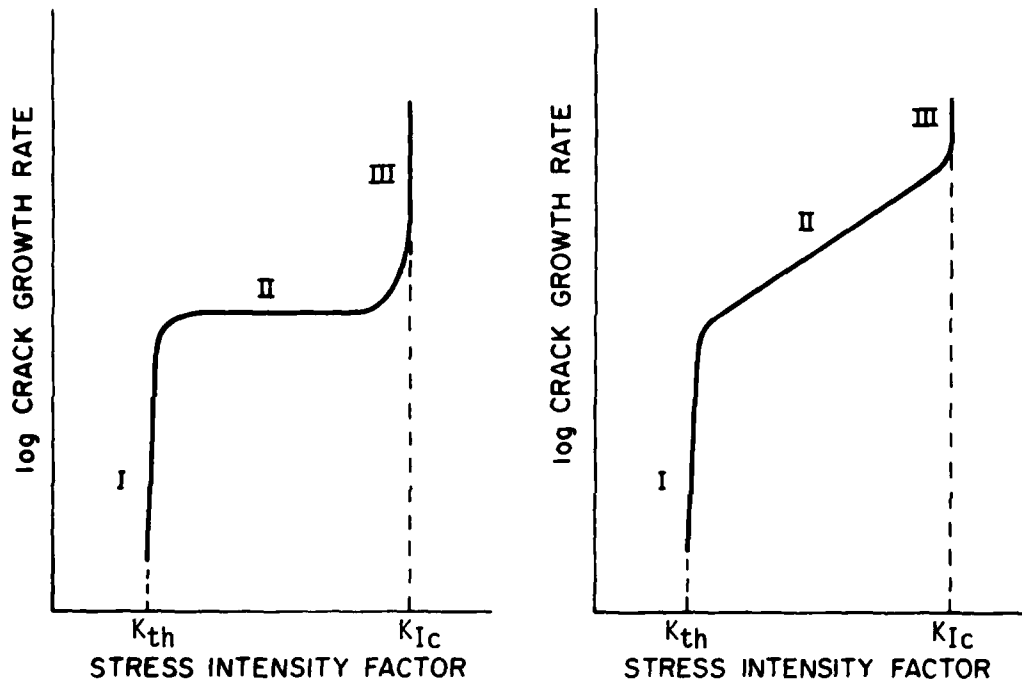


FIGURE 4 Schematic diagram of environmentally assisted crack growth behavior (Williams et al. 1979).

Within the general fracture-mechanics approach for design against environmentally assisted cracking, the threshold and growth-rate parameters are used in different ways to establish design guidelines and rules. When growth rates in the projected service environment are relatively fast (i.e., faster than that which can be tolerated for the required design life), crack growth is not to be permitted, and K_{ISCC} is used to establish acceptable material and loading conditions. When K_{ISCC} is relatively low but the growth rate also is very slow, growth rates alone are used to establish a satisfactory design. Other approaches also are used. For example, the K_{ISCC} approach may be modified by using an operational definition of K_{ISCC} based on a limiting value of growth rate which can be tolerated for the required life. For many critical structural components, there also exist design requirements that restrict the use of any material which exhibits crack extension in a K_{ISCC} test exposed to expected service environments.

Despite the obvious advantages of a fracture mechanics approach to the characterization of environmentally assisted cracking behavior, the existing methodology has several limitations. Certain problems also must be resolved before widely accepted methods can be established for use in design and in material selection. Several matters of concern relate directly to the overall applicability of the basic concepts of fracture mechanics to the environmentally assisted cracking problem. Among these concerns are questions regarding: (1) the existence of a true threshold for environmentally assisted crack growth and the influence of superimposed load fluctuations on this threshold, (2) the applicability of existing fracture-mechanics concepts to the relatively small defects typically of concern in environmental problems, (3) the influence of large-scale yielding, or plasticity, on the measured parameters and on cracking response, (4) the extensive amount of data scatter encountered in testing, particularly in the case of as-welded structures, and (5) methods for the characterization of the effects of residual stress on cracking behavior.

The Threshold K , K_{ISCC}

Ideally, the threshold parameter, K_{ISCC} , is intended to define the combination of applied stress and defect size below which environmentally induced crack extension will not occur under static loading conditions in a given material-environment system. In reality, the reported value of K_{ISCC} for a given system often reflects primarily the initial stress intensity or K_I level and exposure time associated with the testing. More specifically, the initial K_I level can significantly affect incubation time (the time required for crack growth to begin), as noted schematically in Figure 3. Terminating a K_{ISCC} test in the crack-incubation regime, therefore, can lead to a serious overestimate of K_{ISCC} . Incubation time, like K_{ISCC} , is a function of the material-environment system under consideration and can vary considerably (Wei et al. 1972, Clark 1981). Table 1 shows results from increasing K_I or crack initiation tests of a 1240 MPa yield strength, high alloy steel exposed to synthetic sea water at room temperature (Wei et al. 1972). Data in Table 2 are from decreasing K_I or crack arrest tests of a low alloy steel exposed to oxygenated steam at

100°C (212°F) (Clark 1981). A comparison of K_{Isc} obtained by the crack initiation and crack arrest methods on high-strength steels exposed to salt water at room temperature is given in Table 3 (Novak et al. 1978). Note that the apparent values of K_{Isc} from these tests (Tables 1 and 2) are a direct function of test time (or investigator's patience), which reflects the influence of incubation time. When the testing times are sufficiently long and when compatible criteria are used for establishing the threshold, K_{Isc} values determined for increasing- K_I and decreasing- K_I tests may be the same (Table 3). Such results make it clear that when K_{Isc} values are reported, the criterion for their assessment and the exposure time in the environment must accompany the data. In addition, these data suggest that a rational approach to the development of useful information for design is to establish an operational definition of K_{Isc} that is appropriate for the structure under consideration. For example, if the structure of concern could tolerate 25.4 mm of crack growth in a required life of 20 years (an average growth rate of 1.3 mm/yr), it would be necessary only to use an exposure time that is long enough to ensure the growth rate associated with the operationally defined K_{Isc} did not exceed 1.3 mm/yr. Another approach for establishing threshold parameters for design involves testing to exposure times that are equivalent to or longer than the expected service life.

Small-Defect Concerns

The requirements for K_{Isc} tests as well as for other fracture-mechanics tests include very explicit criteria regarding the minimum crack length to ensure that the test results can be analyzed properly using existing linear fracture mechanics concepts (American Society for Testing and Materials 1967, 1979). Specifically, for a compact tension (CT) specimen, the crack length (crack starter notch plus fatigue crack) must be sufficiently long to eliminate any undesirable interaction of the loading arrangement with the crack tip stress field (American Society for Testing and Materials 1979). In addition, the required fatigue precrack must be long enough to eliminate any influence of the crack starter notch. As a result of these requirements, a typical K_{Isc} test uses a relatively large starting crack (on the order of 25 mm long in a 25-mm thick specimen). In actual service however, one is rarely concerned with initial defects of this size. Most often one must assess the performance of structural components containing initial defects with dimensions on the order of the maximum sensitivity of the applicable nondestructive inspection procedure (e.g., surface defects about 0.75 mm deep). In view of the disparity between the crack-size requirements for fracture-mechanics testing and the sizes of cracks involved in potential environmentally assisted cracking problems, it is reasonable to question the applicability of existing fracture mechanics concepts to small flaws. More specifically, it must be determined whether there is a defect size below which conventional linear fracture mechanics concepts cannot be applied. If there is, then such a limitation obviously must be recognized when attempting to conduct a

TABLE 1 Influence of Cut-Off Time on Apparent K_{Isc} Using the Initiation Method

Elapsed Time, hr	Apparent K_{Isc}
	MPa/ \sqrt{m} (ksi/ $\sqrt{in.}$)
100	187 (170)
1,000	127 (115)
10,000	28 (25)

Source: Wei et al. 1972.

Note: Material = 1240 MPa (180 ksi) yield strength, high-alloy steel; environment = synthetic sea water at room temperature; and test = constant load cantilever bend specimens (increasing K_I).

TABLE 2 Results of Long Time K_{Isc} Tests Using the Arrest Method^a

Exposure Time, hr (days)	Crack Extension	Stress Intensity Factor, K_I
	mm (in.)	MPa/ \sqrt{m} (ksi/ $\sqrt{in.}$)
0	0	88 (80)
5,200 (217)	6.6 (0.26)	77 (70)
14,100 (587)	19.8 (0.78)	46 (42)
21,100 (879)	26.9 (1.06)	23 (21)

Source: Clark 1981.

^aMaterial = 1070 MPa (155 ksi) yield strength NiCrMoV Steel (ASTM A471); Environment = 100°C (212°F) steam + 40 ppm O₂; Test = IT WOL Bolt Loaded (decreasing K_I).

TABLE 3 Assessment of K_{Isc} by the Initiation and Arrest Methods

Steel	K_{Isc} - MPa/ \sqrt{m} (ksi/ $\sqrt{in.}$) ^a	
	Initiation	Arrest
10Ni Normal Purity	24 (22)	26 (24)
10Ni High Purity	59 (54)	57 (52)
18Ni (250) Normal Purity	22-33 (20-30)	28 (25)
18Ni (250) High Purity	<33 (30)	<33 (30)

Source: Novak et al. 1978

^aEstimate based on a crack growth rate of 2.5×10^{-4} mm/hr (10^{-5} in./hr).

Note: Environment = salt water at room temperature; test = constant load WOL specimens for initiation and bolt loaded WOL specimens for arrest.

rational, quantitative life-prediction analysis. Clark has addressed this problem for the case of high-strength steels exposed to hydrogen sulfide gas and has reported that as long as the crack is at least 25 times larger than the associated crack-tip plastic-zone size,

$$r_p = \frac{1}{6\pi} (K_I/\sigma_{ys})^2 ,$$

fracture mechanics concepts are directly applicable (American Society for Testing and Materials 1967, Clark 1976). However, based on such a criterion (the only one for which experimental data exist), the direct applicability of fracture-mechanics concepts to many potential environmentally assisted cracking problems is questionable. A graphical representation of the plastic zone size to crack-size criterion proposed by Clark (1981) ($a \geq 25 r_p$) to define the limits of applicability of linear fracture mechanics is given in Figure 5 for several yield-strength levels. Note that based on these data, the smallest surface flaw that could be analyzed by LEFM in a 690 MPa yield-strength steel at an applied-stress-intensity factor of $55 \text{ MPa}\sqrt{\text{m}}$ is about 7.5 mm deep. The fracture-mechanics analysis of defects smaller than 7.5 mm deep under these conditions would be questionable. Such considerations imply that, for a given combination of material and applied stress, there may be a defect size below which a conventional fracture-mechanics analysis would significantly overestimate the defect severity (due to the effect of the plastic zone or free surface yielding on the defect itself). Obviously, such an overestimate would have an important impact on life prediction. The only rational approach to the resolution of this problem is a combined experimental and analytical effort designed to address the concerns noted above.

Plasticity Effects

As discussed previously and in the foregoing subsection on Small-Defect Concerns, the applicability of linear fracture mechanics is predicated on the assumption of small-scale yielding (i.e., when the plastically deformed region ahead of the crack is small in relation to the dimension of the crack and of the body). For lower strength alloys and for alloys that possess high resistance to environmentally assisted cracking, the requirement of small-scale yielding is often not satisfied and cracking is accompanied by significant plasticity in practical specimens and in practice. In these cases the application of linear fracture mechanics is no longer valid and the parameter K_{ISCC} is no longer meaningful. The problem is in part identical to that described before for small defects. New approaches and a redefinition of crack driving force will have to be developed. It is to be recognized that crack growth under conditions of large-scale yielding will likely depart significantly from mode I (i.e., tensile opening mode). The revised crack driving force must incorporate mixed-mode crack growth. In addition, the possible influence of large-scale deformation on crack growth response, reflecting the interactions of the deleterious species with the deformed microstructure, must be considered.

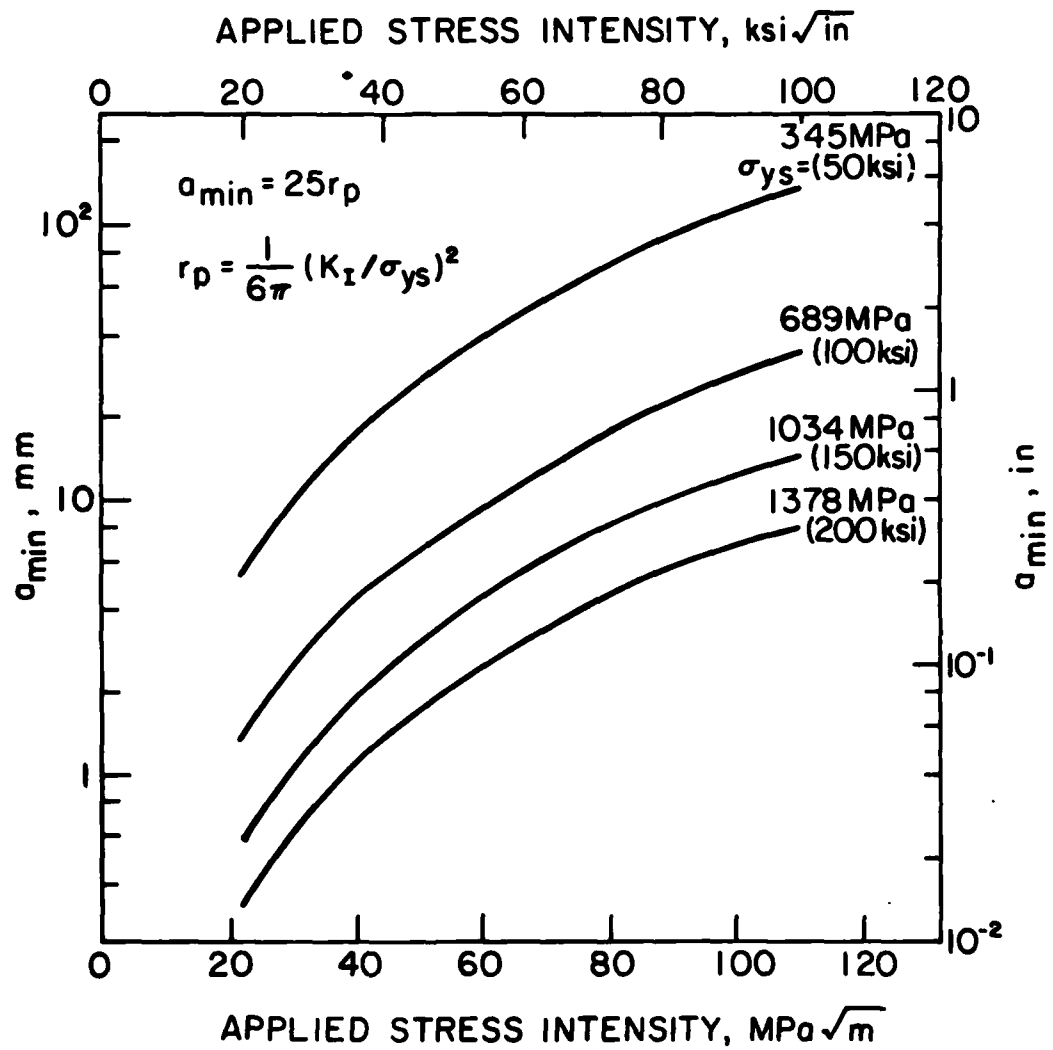


FIGURE 5 Graphical presentation of small defect criterion (Clark 1981).

Data Scatter

Another extremely important area of concern related to the characterization of environmentally induced cracking behavior with precracked specimens is data scatter. In the very few systematic studies that have been conducted to evaluate scatter in K_{Isc} and da/dt data, a significant amount of variability was observed. In an investigation of high-quality type AISI 4340 steel exposed to research-grade hydrogen sulfide gas, more than ± 20 percent scatter in K_{Isc} was encountered with material from the same bar of steel (Clark 1976). Thus, even under ideal conditions, substantial variations in K_{Isc} behavior can be expected. In a round-robin program to evaluate K_{Isc} test methods currently being conducted by American Society for Testing and Materials (ASTM) Committee E24.04.02, data scatter on the order of ± 15 percent (of the average) has been observed (unpublished results of the ASTM Committee E24.04.02, Task Group on Stress Corrosion Cracking Test, American Society for Testing and Materials, Philadelphia, Pennsylvania). Such results indicate that multiple testing is required to develop statistically adequate design information. Obviously, two tests are not sufficient to properly characterize behavior that may involve as much as ± 25 percent scatter. Even more important are questions regarding the procedure for using a design parameter that exhibits such wide variability.

Residual Stresses

The potential role of residual stresses on environmentally assisted cracking behavior in as-welded steel structures is perhaps the single most complicating aspect of designing against corrosion damage. Because of the inability to accurately measure the magnitude and orientation of residual stresses in welded structures, a common practice is to assume the presence of yield-point tensile stresses oriented perpendicular to all defects in the vicinity of the weldment. Such an assumption is likely to be extremely restrictive but is presently unavoidable. An alternative to this approach is full-size-model testing of the as-welded components—usually a very expensive endeavor. The prospect for the development of improved methods for dealing with the influence of residual stress on environmentally assisted cracking behavior in welded structures appears to be poor until improved methods become available for accurately measuring residual stresses.

STATE OF THE ART OF TEST METHODS

Various types of specimens and methods of loading can be used to determine the environmentally assisted cracking response of materials. LEFM test methods have been under development for over a decade. Unfortunately, agreement has yet to be reached on the adoption of a consensus standard, even though a considerable amount of effort has been expended in test method development and cooperative evaluations (unpublished results of the ASTM Committee E24.04.02, Task Group on Stress Corrosion Cracking Test, American Society for Testing and Materials, Philadelphia, Pennsylvania). The problem in reaching a consensus lies not so much in questions of approach and of the analytical basis but in the experimental fulfillment of the basic assumptions of the

analysis and in reconciling the chemical-mechanical-metallurgical interactions. Nevertheless, the methodology is sufficiently well developed and is in use. The state of the art of these methods is summarized below.

The fracture-mechanics-based specimens may be broadly classified into three groups:

1. Constant-load, increasing- K_I specimens,
2. Constant-displacement, decreasing- K_I specimens, and
3. Constant- K_I specimens.

The first group of specimens is exemplified by the cantilever-bend specimen (Brown 1972, Brown and Beachem 1965); the second, by the bolt-loaded wedge-opening loading (WOL) or compact tension (CT) specimen (Novak and Rolfe 1970); and the third, by tapered double-cantilever-bend (DCB) specimen subjected to constant applied load (Marcus and Sih 1971). By judicious placement of loads and choice of loading conditions or by the use of computer control (programmed loading), increasing- or decreasing- K_I conditions may be obtained for any of these specimen groups. Specimens from the first two groups have been used widely for kinetic studies and for K_{Isc} determinations, and those from the third group have been used for kinetic studies when a constant- K_I condition is required.

For K_{Isc} determinations using the increasing- K_I specimens, a crack-initiation criterion is used (Brown 1964, Novak 1977, Wei et al. 1972). With the decreasing K_I specimens on the other hand, a crack arrest criterion is used (Novak 1977, Novak and Rolfe 1970, Wei et al. 1972). This arrest criterion usually is defined in terms of some reliably measurable "final" crack-growth rate to ensure the approach to crack arrest (e.g., from 2.5×10^{-8} to 2.5×10^{-7} m/hr) (Novak 1977). In either case, valid measurements of K_{Isc} depend on overcoming the so-called incubation period, which can range from a few seconds to over 10,000 hr depending on the particular combination of environment and material and test conditions under investigation.

For kinetic measurements (i.e., growth rate versus K_I), any of the specimen types and loading procedures may be used. Current emphasis is on the measurement of steady-state response where there is a one-to-one correspondence between the rate of crack growth and the crack driving force, characterized by K_I , although nonsteady-state crack growth may be of considerable interest in the overall service performance (Wei et al. 1972). Within the context of steady-state measurements, the presence of nonsteady-state growth may be more readily identified when constant- K_I and decreasing- K_I types of loading are used, but several specimens may need to be utilized at different starting K_I levels to isolate the contributions of nonsteady-state crack growth for increasing- K_I tests. For both K_{Isc} and kinetics measurements, the LEFM requirements that govern the methodology must be satisfied. These requirements, by and large, are well understood. It is also essential that the potential influence of nonsteady-state response, including the

phenomenon of incubation, be understood and be taken into account in testing as well as in design. This latter requirement is most troublesome and least understood, and it remains to be the key barrier to the development of acceptable test methods and of the appropriate design methodology.

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Chapter 4

VARIABLES THAT INFLUENCE ENVIRONMENTALLY ASSISTED CRACKING RESPONSE

Environmentally assisted cracking response reflects the synergistic interactions of the material with the applied load and the external chemical environment and is therefore influenced by mechanical, geometrical, environmental, and metallurgical variables. To better appreciate the problems associated with the development of test methods and the utilization of experimental data in design, the influences of these variables need to be recognized and understood. Some important variables are discussed briefly below.

MECHANICAL AND GEOMETRIC VARIABLES

In addition to the obvious influence of applied stresses (or stress-intensity level) on environmentally assisted cracking behavior, there are other mechanical and geometric loading variables that can be extremely important. A discussion of the parameters likely to be most significant in high-strength steel weldments is presented below, along with a brief review of the primary variable (i.e., stress-intensity factor).

Stress Intensity Factor, K_I

The crack-tip stress-intensity factor, K_I , is used to characterize the mechanical driving force for crack growth. Its use is predicated on the assumption of limited plasticity and has been well justified (Johnson and Paris 1968, Wei 1969, and Wei et al. 1972). For consistency and for many applications, the additional condition of "plane strain" is imposed. The applicability of the approach and the meaningfulness of results depend on the experimental fulfillment of the basic assumptions and conditions, which are met principally by the use of sufficiently large specimens. These requirements are generally well recognized by most investigators even in the absence of a consensus standard. In addition, K_I governs the effective opening of the crack. It affects, therefore, the access and transport of the deleterious environment to the crack tip and thereby influences the local chemistry and cracking response. The effective value of K_I may be affected by a number of secondary factors, such as prestressing and corrosion product wedging, which are considered in the following subsections.

Prestressing

The terms "prestressing" or "prior loading" as used here refer to any loading encountered by the component prior to its normal service. Loading associated with manufacturing (shrink fitting, cold working, etc.), shipping, and proof testing would fall into this category. Regardless of the source, prestressing of a component can have a significant effect on subsequent environmentally assisted cracking behavior. For example, work conducted by Carter (1970) has shown that prior tensile loading in air can increase the measured value of K_{ISCC} for type 4340 steel exposed to seawater by at least a factor of two. Questions regarding the potential effect of prestressing in the actual environment of interest remain unresolved. However, available data show significant effect of prior loading on fatigue crack-growth behavior, and it is not unreasonable to expect similar behavior for environmentally assisted cracking under sustained loads.

Loading Rate, Wave Form, and Dwell Time

Loading rate and loading wave form (loading ramp shape) are expected to have a significant effect on environmentally assisted cracking behavior. This expectation is based on corrosion-fatigue data that clearly show the influences of these parameters on cracking performance (Barsom 1972). For very rapid loading (high frequency) and very steep loading ramps, the environment appears to have no effect on fatigue crack growth. In fact, for certain material-environment systems, corrosion-fatigue tests using square-wave loading produced much smaller enhancement in crack-growth rates than those obtained under sine-wave loading at the same frequency and stress level. Such behaviors suggest questions regarding the ability to predict environmentally assisted cracking performance. For example, does a rapidly loaded K_{ISCC} test permit the development of sufficient crack tip damage during loading to represent actual components that may require several hours to reach maximum load?

Effects of Periodic Loading

Although this report is not intended to address corrosion-fatigue behavior, the question of periodic loading must be considered. Specifically, does the long time, sustained-load K_{ISCC} test truly represent the behavior of an actual component that may encounter periodic cycling or minor fluctuations in load about an essentially constant mean stress? Work by Fessler and Barlo (1979) has shown that small fluctuations in loading (amounting to ± 1 to 5 percent) can significantly reduce the threshold stress and the apparent environmental cracking threshold K_{ISCC} value for a low alloy steel exposed to a sodium carbonate-bicarbonate solution. These results are shown in Figure 6 and imply that the effect of periodic loading, even at very small stress levels, can alter significantly the environmentally assisted cracking behavior. Consequently, the role of such loading must be considered in developing data and in designing against environmentally assisted cracking.

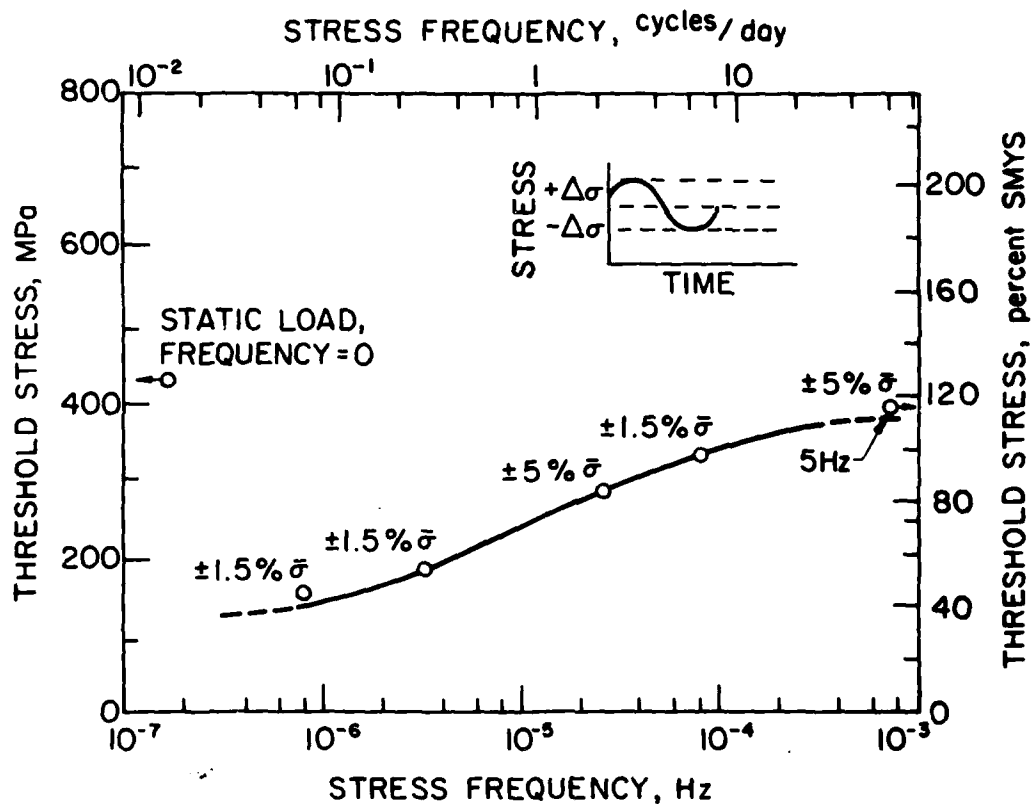


FIGURE 6 Effect of stress fluctuations on the threshold stress for precracked cantilever-beam specimens of X52 pipe in a 1N Na_2CO_3 -1N NaHCO_3 solution at 80°C and -650 mV (SCE) (Fessler and Barlo 1979).

Geometric Effects

A unique feature of the fracture-mechanics approach to the design against structural failure is the ability to incorporate geometric factors (loading configuration; component geometry; and defect location, shape, and size) into the analyses. In the characterization of environmental cracking behavior, however, this unique feature may be mitigated by other geometry-related factors, some of which have been identified on the basis of several recent observations.

One of these observations involves the difference between K_{ISCC} and da/dt values determined with increasing- and decreasing- K_I tests. Comparison of results, developed with constant load, cantilever-bend tests (increasing- K_I with crack extension) and with constant-displacement, compact-tension tests (decreasing K_I with crack extension) for the same material-environment systems do not appear to agree (Clark 1981). Here the decreasing- K_I or crack-arrest test yielded a K_{ISCC} value that is either higher or lower than that obtained from a constant-load test. Other tests, on the other hand, suggest that there is no apparent difference between K_{ISCC} values obtained by the two different procedures (Novak et al. 1978). The reasons for the observed difference in K_{ISCC} have not been adequately established. One important factor appears to be the extent of crack branching encountered in each test. The crack-arrest test, being generally more prone to crack branching, tends to indicate a higher apparent value for K_{ISCC} . Other factors involve corrosion-product wedging and the influence of crack length on solution chemistry at the crack tip, with the resulting impact on the apparent K_{ISCC} . Detailed investigation of this phenomenon is required to adequately resolve this testing problem. Meanwhile, it is important to use a test that matches the type of loading to be encountered in service.

Other observations suggest the potential influence of stress or strain gradient associated with different loading conditions (e.g., tension versus bending) on crack-growth response. Presently, it is believed that the deleterious species in the environment or those produced by reactions with the environment enter the metal through the highly strained region near the crack tip. Their entry and mobility are expected to be influenced by the local stresses and strains. If, on the other hand, access is possible through other regions of high strain, then the loading configuration itself may become important. For example, uniaxial tension, because the net section is uniformly strained, may provide greater access to the damaging environment than bending where less material is under high strain. Although this hypothesis is clearly speculative at this point, there is some evidence to show a difference in environmentally assisted cracking behavior for uniaxial-tension and bend-test specimens, both under increasing- K_I conditions (Clark 1981). The potential influence of loading configuration needs to be considered.

State-of-Stress and Plasticity Effects

Characterization of environmentally assisted cracking performance through K_{ISCC} and da/dt versus K_I requires that linear-elastic fracture mechanics and plane-strain conditions are satisfied. Existing data show that cracking can occur under conditions that deviate substantially from plane-strain (decreasing thickness) and that it is by no means limited to, or is most severe under plane-strain loading conditions (Clark 1981, Novak 1973 and 1981). For low- and intermediate-strength steels, environmentally assisted cracking has been shown to occur under plastic (large-scale yielding) conditions (Novak 1973 and 1981). Clearly, state-of-stress considerations must be addressed in the evaluation of environmentally assisted cracking performance. As a minimum, laboratory tests must exhibit the same state as that for the intended application, and most often this criterion is easily met. Problems can and do arise, however, when the application involves the development of cracks within an existing region of stress concentration. In this case, sufficient plasticity may exist near the stress concentrator such that non-plane-strain and inelastic conditions prevail, and the propensity for cracking cannot be represented by a conventional K_{ISCC} test. Environmentally assisted cracking in the vicinity of a stress concentration, therefore, needs to be addressed in developing rational life prediction procedures.

Mixed-Mode Loading

Because environmentally assisted cracking often occurs intergranularly and because the local stresses are not always oriented perpendicularly to the crack plane, mode II and mode III loading may be present at the crack tip in addition to mode I. The combined loading may alter the crack-growth direction and affect crack-growth response. A quantitative assessment of its influences needs to be made.

ENVIRONMENTAL VARIABLES

It is rather broadly recognized that environmental variables can have a profound effect, both detrimental and beneficial, on tendencies for stressed alloys to crack. The major environmental variables, some frequently neglected, are pH, the nature and concentration of anions and cations in aqueous solutions, the partial pressure and nature of species in gaseous mixtures, electrochemical potential, and temperature.

Each or a combination of a number of the environmental variables can affect the thermodynamics and kinetics of the electrochemical processes that control environmentally assisted fracture. They can affect the thermodynamics of the processes occurring at a crack tip surface by bringing its environment into a regime where, for example, the production of embrittling hydrogen atoms becomes possible, metal dissolution takes place, or passive film formation becomes impossible and crack blunting results. The kinetics of the cracking process are controlled by environmental variables through their effect on the following two interacting factors:

1. The rate of repair of broken protective films (repassivation rate) because the time that the crack-tip surface is exposed to the crack-tip environment determines whether enough embrittling hydrogen atoms can enter the metal lattice or whether sufficient metal atoms can dissolve to produce an unacceptable crack growth rate, and

2. The properties of the protective films developed on a crack-tip surface in the crack-tip environment, because the ability of these films to resist and delay their chemical or mechanical breakdown determines whether sufficiently rapid repassivation rates will be required to produce low crack-growth rates.

There exist a number of electrochemical tests that measure the effect of environmental variables on breakdown and repassivation rates. Environmental variables generally will change from that existing in ambient environments (especially with regard to concentration) when one examines the highly restricted localized environment found in cracks. This is so because diffusion of ions in and out of the restricted confines of a crack (called "occluded cell" by B.F. Brown) is difficult and concentrations of these ions or other species can be built up or decreased. In spite of the fact that the crack-tip environment may differ drastically from an ambient environment, many test methods ignore this difference. Not only does the concentration of important deleterious species such as chloride ions and hydrogen ions go up, but oxygen concentrations go down. The potential can be altered in still poorly understood ways, and the frequently neglected variable of environmental viscosity (thick syrupy solutions may develop) may go up. In developing reliable test methods, especially accelerated ones, the question regarding whether an environment that closely simulates that in a crack should be used is still unanswered. One might question whether an analogous worst-case test environment that simulates the crack tip environment can be employed since the precracked specimens represent the ultimate in stress raisers for fracture-toughness testing regardless of alloy. Unfortunately, however, not enough is known to determine whether the use of such a worst-case environment can be found to be defensible. Were use of such an environment found to be worthwhile, accelerated test methods using simulated crack-tip environments could be used to develop information for designers. Of course, a first step would be to characterize carefully the crack environment, and only some of the needed information now exists. Information about one environmental factor, potential, would come out of this characterization; it is a factor that usually is neglected. A knowledge of the potential at the crack tip and a more thorough understanding of whether a critical potential below or above which failure does not occur could be of great value in designing systems made of alloys whose potential in the ambient environment brings the potential at the tip of a crack to a safe value. Obviously, cathodic or anodic protection is another way to control the environmental variable of potential. What is needed from research and testing, however, is knowledge of what is a safe potential, and if, indeed, such a potential exists.

Knowledge about the nature of the corrodent within the chemical process zone of stress corrosion cracks is highly incomplete and almost without independent verification. If more were known about this local corrodent, at initiation as well as during propagation, perhaps it would be possible to truncate appreciably the holding time needed for initiation. Efforts should therefore be promoted to learn more about the nature and properties of this local corrodent.

For testing in seawater or environments that simulate seawater, a number of other specific considerations must be mentioned:

1. A chloride environment is essential for at least some of the applications. This has been provided traditionally by 3-1/2 percent NaCl in water, and probably much useful information can be gained in the future using such a solution. The chlorinity of this solution approximates that of average seawater. No reason is known to go to a higher chlorinity, and, in fact, the corrosion rate of iron and the stress corrosion rate of 7075 aluminum alloy are at maximum at approximately this chlorinity.

2. If fluctuating loads are involved and if cathodic protection is also involved, it is imperative to use seawater. The reason for this is that, depending on temperature and potential, calcareous deposits may form within the crack and affect growth rate by interfering with crack closure. These deposits form from seawater but not from NaCl solutions.

3. Sulfide contamination of harbor water in which ships have been outfitted has been blamed for serious pitting corrosion of the ships cupronickel condensor tubing (LaQue 1973). Whether such contamination can have a large effect on the environmental cracking of high-strength steel weldments is not known, but, at some stage, it must be addressed experimentally.

METALLURGICAL VARIABLES

Environmentally assisted cracking in high-strength steels and in high-strength steel weldments has been alternatively ascribed to anodic dissolution or to hydrogen embrittlement. However, whether either mechanism is in fact controlling, several metallurgical parameters appear to be common to environmental cracking. For example, in fully martensitic alloys, whether only quenched or quenched and tempered, cracking generally follows prior austenite grain boundaries in unwelded steels (generally called intergranular). In welded steels, intergranular fracture also is observed although in some cases significant amounts of transgranular cracking also are present. The link between these fractographic observations and alloy macro and micro compositional variations is not well understood.

Base Metal

It would be impossible in the scope of this report to review the entire metallurgy of high-strength steels, particularly as it is related to environmentally assisted cracking. However, several general observations must be made. For example, high-strength steels generally are quenched from austenitizing temperatures in order to produce martensitic structures. Austenitizing times and temperatures control the subsequent "prior austenite" grain size and, in general, small grains appear to lead to increased environmentally assisted cracking susceptibility because of the existence of an easier crack-propagation path. Similarly, textures that lead to easier linking of microcracks through grain boundaries lead to increased susceptibility. These generalities, however, are simplifications and several other metallurgical variables also must be considered. For example, even in rapidly quenched steels, other phases often are identified and their roles in environmentally assisted cracking are not at all understood. Some metastable austenite, for example, often is observed. If austenite is retained, several reports have indicated that this phase is beneficial both for general toughness and for environmentally assisted cracking resistance. Additionally, depending on quench rates, quasi-equilibrium phases such as ferrite and cementite may be present that also should lead to improved environmentally assisted cracking resistance although the amounts and distribution of such phases may be difficult to control or even identify. Bainite also is often observed in quenched structures, and, again, the effects of amounts and distributions have not been sufficiently characterized. At the present time only tenuous correlations of these effects have been presented. The metallurgical problems may become further complicated when steels are tempered to improve toughness.

In addition to these rather gross metallurgical parameters, the additional problem of microsegregation of trace elements (called tramp elements if they reduce toughness) occurs in commercial steels and can affect environmentally assisted cracking response (Table 3) (Novak et al. 1978). These elements often are associated with the phenomenon of temper embrittlement and some investigators have made attempts to correlate this phenomenon with environmentally assisted cracking. The elements that have traditionally been associated with temper embrittlement include As, P, Sb, Sn, etc., and they are thought to be preferentially segregated to grain boundaries during tempering. Auger electron spectroscopy has been utilized to analyze fracture surfaces of embrittled steels, and these investigations have shown that embrittlement may occur when only a partial monolayer of coverage is observed. However, it should be emphasized that a direct correlation between temper embrittlement and environmentally assisted cracking has not been firmly established, and further investigation is required prior to establishing a definitive link. This statement pertains not only to the general concept of microsegregation, but also to which elements actually are damaging.

Weldments

Joining of high-strength steels by welding introduces a number of further complications in determining metallurgical effects on environmentally assisted cracking resistance. In the general case the process of welding introduces at least three metallurgically different regions--the fusion zone, the heat affected zone, and, of course, the base metal. For some structures there is almost a discontinuity between each zone with relatively narrow boundaries that may be delineated clearly. In other steels, however, the boundaries may be quite diffuse and a continuum structure exists between each portion of the steel. This is particularly true when thick plates are welded since multipass welds are required. The microstructure in and near the weld is further affected by the heating pattern and the cooling rate. Accordingly, such variables as the energy input (including time and temperature of preheat); the welding process; and the size, type, and metallurgy of the electrode must be considered. Additional variables including the polarity, arc length, weld pass rate, and the number of passes also must be considered. All of these variables are equivalent to relatively uncontrolled heat treatments. Not only are these heat treatments uncontrolled, but they will vary with subsequent weld passes since cooling rates will be interacting functions of plate thickness, number of weld passes, etc. To further complicate the issue, weld rod materials of different composition from the plate material often are specified, thus creating a continuum in alloy composition and, accordingly, phase amounts and distribution and microsegregation from the fusion zone into the base plate.

Commentary

In light of these considerations and the unknown relationships discussed in the previous sections, it appears that thorough understanding of environmentally assisted cracking in welded structures is, at best, a difficult task. An understanding of the role of metallurgical variables in environmentally assisted cracking in these structures from first principles is impossible given the current state of knowledge. Accordingly, it is suggested that only a qualitative comparison of metallurgical structure is possible in the short term. For the near future, only direct comparison between base metal and weld metals of known chemistry is possible. Extreme care must be taken to ensure that welding variables are carefully and reproducibly controlled and that they model actual field welding practice as closely as possible. In the meantime, it is hoped that the large amount of ongoing research of the environmentally assisted cracking of high-strength steels will enable the reduction of what appears to be an almost infinite matrix of metallurgical variables to an acceptable evaluation program. This latter term should be emphasized since it is unlikely that a detailed scientific research program in the area of environmentally assisted cracking of high-strength steel weldments will yield significant practical technical advances for the near term. Rather, a carefully conducted, empirically sound, comparative evaluation of a reasonable number of parameters is most likely to result in welding practices that will produce materials sufficiently resistant to environmentally assisted cracking.

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Chapter 5

VARIABILITY AND PROBLEMS IN THE MEASUREMENT OF ENVIRONMENTALLY ASSISTED CRACKING RESPONSE

The state of the art for linear fracture mechanics test methods used in evaluating environmentally assisted cracking response has been summarized in Chapter 3. Although a consensus standard has not been adopted as yet, the methodology is sufficiently well developed and many of the problem areas are reasonably well defined. Before considering the problems associated with testing of weldments and those associated with the extension of this technology to structural design, a review of the sources of variability and of problems in the measurement of environmentally assisted cracking response of base metal is appropriate.

To better appreciate the causes for variability and testing problems, it is essential to understand that environmentally assisted cracking involves complex chemical-mechanical-metallurgical interactions and to recognize the ability and willingness of investigators to deal effectively with them. These interactions manifest themselves in the phenomena of nonsteady-state crack growth (Wei et al. 1972), which include transient crack growth, incubation, and crack acceleration. These phenomena are functions of crack-tip chemical environment, K_I level, and materials variables, all of which are not fully understood. They impose conditions of test (e.g., test duration) that are different for different material-environment combinations and that cannot be defined a priori. In fact, the question of appropriate test durations for the different material-environment combinations and the apparent need to establish them experimentally on a case-by-case basis have been the major stumbling block in the adoption of a recommended test method by ASTM Committees E-24 on Fracture Testing and G-1 on Corrosion.

The question of variability, from the viewpoint of test methods, needs to be placed in proper perspective. It is important to distinguish between variability that is associated with a test method or procedure and the inherent variability in a material and its susceptibility to an environment. Suitable test methods must minimize the former and allow for quantitative assessment of the latter. This important issue on variability has not been adequately addressed, and sufficient attention and recognition have not been given to the fact that some of the current test methods do not allow for the quantitative assessment of variability from either source.

VARIABILITY

Variability in the measured values for environmentally assisted cracking response arises from two primary sources: uncertainties associated with the measurement methods, and variations in materials and local environment. Needless to say, the principal objective is to minimize the contributions from the first source and to quantify those from the second source in a way that would be useful for design (e.g., in terms of extreme-value statistics). This is not a trivial problem. Acceptable methods for assessing the contributions of each source do not exist, and some of the measurement errors cannot always be quantified.

For K_{Isc} measurements, the contributions to variability from experimental methodology include:

1. Criterion to establish when crack growth had taken place for the crack-initiation tests.
2. Criterion to ascertain that cracking had indeed arrested in the case of crack-arrest tests.
3. Accuracy of the K calibration as a function of crack length.
4. Ability to measure crack length reliably and accurately, particularly in the presence of general corrosion.
5. Methods for assessing the value of K_I at crack arrest (e.g., experimental determinations of final load or inference of final load on the basis of approximate analyses).
6. Corrosion-product wedging and its effect on K_I and on chemistry at the crack tip.
7. Changes of crack tip environment with time.

One of the more significant sources for error lies in the choice of test duration. This choice is dictated by considerations of incubation and crack-growth kinetics, which are functions of the mechanics-metallurgy-chemistry interactions and cannot be prescribed a priori. Too short a test duration can lead to an overestimation of K_{Isc} and to significant difficulties in predicting performance (Tables 1 and 2).

Many of these considerations of variability apply also to the measurement of crack-growth kinetics. In addition, variability may be introduced through improper accounting for the presence of nonsteady-state crack growth. It can be significantly altered by the choice of crack-length measurement interval relative to measurement precision and the methods used in calculating crack growth rates from the primary (crack length versus time) data (Novak 1977, Wei et al. 1979), as well as by the precision in measuring-time intervals. The precision in both measurements can depend on growth rate (i.e., on the time available for measurement) and must be assessed. Precision in crack length measurements depends on: (1) resolution of the measuring instrument, (2) ability to resolve the crack tip, (3) amount of time available for making measurements (i.e., crack speed), and (4) local disturbance in crack front. This measurement precision is essentially independent of time (i.e., of item 3) for growth rates of practical interest. By the same token, precise measurements of time can be expected, except at the very fast growth rates. A perspective on the problems for reliable

measurement of rates can be obtained by considering the following example, where crack growth rate is to be computed by the finite difference method (i.e., $da/dt \approx \Delta a/\Delta t = (a_{i+1} - a_i)/(t_{i+1} - t_i)$). If one assumes a measurement precision (say, 3 standard deviations) of 10^{-4} m, with precise measurement of time, then a crack-growth increment $\Delta a = 10^{-3}$ m must be used to ensure that the error propagated into the computed da/dt is within ± 20 percent. (The use of a fixed growth increment is preferred so that on average the microstructural features sampled for each rate measurement will be the same.) To accomplish this objective, crack-length measurements need to be taken hourly for an expected growth rate of 10^{-3} m/hr, every 100 hr at 10^{-5} m/hr, and every 10,000 hr at 10^{-7} m/hr. Obviously, large numbers of replicate measurements at the very slow rates become impractical, and application of rate criteria to K_{ISCC} determinations must be tempered also by these considerations. The methods used in computing da/dt from the (a,t) data also can affect variability and introduce bias and must be carefully evaluated (Novak 1977, Wei et al. 1979).

Because of some of the difficulties in identifying and controlling variability from the experimental methods, quantitative assessments of variability introduced by differences in materials and environments are not available. It is recognized that the material- and environment-related variabilities do exist and do play an important role in reliability assessments. It must be recognized also that in crack-initiation tests, such as tests of cantilever-bend specimens, K_{ISCC} is estimated from a number of tests at different initial K_I levels. As such, the value contains engineering judgment and would not be suitable for use in statistical analysis. Crack-arrest tests, on the other hand, provide one value of K_{ISCC} for each test specimen, which can be computed on the basis of some prescribed objective standard. These specimens, therefore, are more suitable for use in assessing variability in the threshold K_I (i.e., K_{ISCC}). Because the measured data are to be used in estimating performance, often for times that are one or more orders of magnitude longer than the test durations, quality data and reliable determinations of variability are essential. Reliable methods for extensive extrapolation of experimental data, based on understanding of the governing mechanisms, will be needed.

TESTING PROBLEMS

Testing problems in the measurement of environmentally assisted cracking response may be separated into two groups: those associated with the measurement of threshold (i.e., K_{ISCC}) and those associated with the measurement of kinetics (i.e., da/dt versus K_I). These problems will be listed and described, with annotations, by Novak in a forthcoming paper. Many of the problems pertain to experimental methods and can be readily resolved. Some of the problems, such as those related to test duration, incubation, and nonsteady-state crack growth, cannot be treated on an ad hoc basis. Their resolution will require a more complete understanding of the chemical-mechanical-metallurgical interactions and certainly a willingness to accept much longer test

durations (tailored to specific material-environment combinations) than those used heretofore. The need for additional research to better define these requirements is discussed in Chapter 6.

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Chapter 6

PROBLEMS AND NEEDS

In this chapter, a brief discussion of problems and needs for additional work to bring the state of the art in materials testing and in design for resistance against environmentally assisted cracking to a level that is consistent with those for fracture is presented. The discussion pertains not only to high-strength steel weldments but more broadly to environmentally assisted cracking of other high-strength structural alloys. In the first part, problems and needs associated with sustained loading (i.e., stress-corrosion cracking) are considered. In the second part, the more complex case of environmentally assisted cracking under fluctuating load (i.e., corrosion fatigue) is addressed.

SUSTAINED-LOAD CRACKING

Some of the problems associated with the assessment of environmentally assisted cracking susceptibility of base materials have been discussed previously. These problems pertain to the assessments of weldments as well but are exacerbated by the presence of residual stresses (of varied intensity and direction) and heterogeneous microstructure in weldments. Without delving into the specifics of the individual problems, five fundamental problem areas appear to require attention:

1. Chemical-metallurgical-mechanical synergism,
2. Small defect (micro versus macro) behavior,
3. Inhomogeneous microstructures and residual stresses,
4. Load fluctuations, and
5. Statistical analysis of data and modeling.

Chemical-Metallurgical-Mechanical Synergism

The problems of test duration, nonsteady-state cracking response, etc. are intimately tied to the processes that take place near the crack tip. These processes involve the transport of the environment (including specific ions), reactions at the crack tip, transport of deleterious species through the material, embrittlement or dissolution, etc. Without detailed fundamental understanding of the relevant processes, rational judgment for the appropriate test durations and other decisions on test methodology and design cannot be made. In the absence of this understanding, decisions need to be made on an ad hoc basis and must be supported by sufficient experimental evidence. A cursory review of past programs suggests that this work has not been done and that it must be carried out to ensure the orderly development of a rational methodology

for materials evaluation and design. Fundamental understanding also is needed for modeling cracking response, which is essential for the development of predictive methodology.

Small Defect (Micro versus Macro) Behavior

To properly consider environmentally assisted cracking response, the issue of crack initiation and crack growth should be addressed. Even if one can circumvent the issue of crack initiation, it is still necessary to consider the progression of the crack from a very small size (for which the applicability of continuum analysis, such as that used in LEFM, is questionable) to some larger size to precipitate fracture. Crack dimensions also can influence the chemistry and electrochemical potential near the crack tip and, therefore, affect cracking response. Work designed to address the mechanics and the chemistry aspects of the problem is needed.

Inhomogeneous Microstructure and Residual Stresses

Inhomogeneous microstructure and residual stresses present special problems for the assessment of cracking responses of weldments. With respect to inhomogeneous microstructure, the issue appears to be principally one of sampling. Adequate numbers of tests must be carried out to provide a reliable and representative data base for design analysis and judgment. The treatment of residual stresses, however, is less clear. From a mechanics viewpoint, residual stresses are to be considered as perturbations to the local crack driving force and should be treated as such. Because of the complex distributions in magnitude and orientation (which cannot be determined practically), the presence of these stresses often is considered as a part of the material's response during evaluation. On the other hand, they are commonly considered as a part of the driving force in considering failure. Work is needed to resolve this inconsistency and to arrive at a rational basis for incorporating the influences of residual stresses and heterogeneous microstructures.

Load Fluctuations

Even though the applied load may be considered to be constant in the design and operations of many structures, minor load fluctuations often are encountered during service. Periodic major load changes, such as those associated with start-up and shut-down, also may occur during the life of a structure. From the perspective of sustained-load cracking, these load fluctuations are viewed as perturbations that reduce the environmentally assisted cracking threshold, K_{Isc} . On the other hand, these minor fluctuations of up to ± 5 percent about the applied load would correspond to the case of fatigue loading at a load ratio R (i.e., the ratio between the minimum and maximum loads in one cycle of loading) of 0.9 or higher. In this context, these fluctuations transform the problem into one of corrosion fatigue and should be considered as such. Because fatigue crack growth can indeed occur at $R = 0.9$, K_{Isc} ceases to have meaning, and a reduction in the apparent value should come as no surprise and can be understood through a simple change in perspective.

Statistical Analysis of Data and Modeling

It is to be recognized and accepted that there are inherent variabilities in the cracking response of materials and particularly of weldments. Adequate amounts of data must be obtained to ensure proper characterization of response. Methods must be developed to isolate the contributions of experimental methods from those of materials and environments and to provide quality data for life predictions. Modeling of cracking response must be developed, on the basis of fundamental understanding, to permit reliable estimations of service performance at lifetimes that extend one or more orders of magnitude beyond the time that is available for materials evaluation (e.g., 30-year service versus 1 to 2 years for material characterization). Major support for this type of effort is needed urgently if significant progress is to be made.

FATIGUE CRACKING

Because of the presence of load fluctuations on most structures, one should logically consider corrosion fatigue as a potential cause for failure. Recent research has shown that environmentally assisted cracking under sustained load and in fatigue may be considered as a continuum, at least with respect to crack growth. Cracking response in terms of frequency and pressure, for the case of gaseous environments, has been readily explained in relation to understanding that has been developed from studies of sustained-load crack growth (Wei and Simmons 1980, Weir et al. 1980). Additional experimental data now suggest that quantitative understanding of fatigue crack growth response in aqueous environments can be expected from coordinated chemistry, mechanics and metallurgy studies (unpublished results, G. Shim and R.P. Wei, Lehigh University, Bethlehem, Pennsylvania, 1981). Detailed consideration of environmentally assisted fatigue crack growth is beyond the scope of this report. The essential point is that this is an important aspect of the overall problem of environmentally assisted cracking of high-strength alloys, perhaps more important than cracking under sustained loads. In spite of its apparent complexity, it must be addressed and very soon. Available evidence suggests that the problem is tractable.

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APPENDIX

Curricula Vitae of Committee Members

ROBERT P. WEI is a Professor of Mechanics at Lehigh University, Bethlehem, Pennsylvania. He received his B.S., M.S., and Ph.D. degrees from Princeton University in 1953, 1954, and 1960, respectively. He has served as Instructor at Princeton and was affiliated with the applied Research laboratory of the U.S. Steel Corporation before joining the staff at Lehigh in 1966. His principal research activities involve the development of fundamental understanding of the mechanical, metallurgical and chemical aspects of subcritical crack growth in aluminum, titanium and ferrous alloys. Professor Wei is a Fellow of the ASTM and has been active on many ASTM committees concerning fatigue and fracture. Presently, he is chairman of Committee E9.01 on Fatigue Research. He received an ASTM Award of Merit in 1978. Professor Wei was co-recipient of the Henry Marion Howe Medal of the American Society of Metals for 1979.

B. FLOYD BROWN was close to Navy problems through 18 years at this U.S. Naval Research Laboratory where he was responsible for marine corrosion programs. From 1973 until his untimely death this year he was a Senior Research Scientist in the Department of Chemistry at American University. In addition to outside consulting, he was a member of the Corrosion Advisory Committee of the Electric Power Research Institute. Dr. Brown was on active duty in World War II with the U.S.N.R., discharged with the rank of lieutenant.

W. G. CLARK, JR. is Manager of Materials Reliability Research at the Westinghouse Research and Development Center. He received a B.S. in Metallurgical Engineering in 1963 and an M.S. in Materials Engineering in 1968 from the University of Pittsburgh. Mr. Clark currently directs research in the areas of fracture mechanics, failure analysis and the nondestructive characterization of structural materials. He is an expert in the application of fracture mechanics to structural risk assessment. Mr. Clark is a past chairman of ASTM Subcommittee E24.04 on Subcritical Crack Growth. He received the ASTM Award of Merit in 1979 and he is a registered professional engineer in the state of Pennsylvania.

D.J. DUQUETTE is Professor of Metallurgical Engineering at Rensselaer Polytechnic Institute, Troy, New York. He received his B.S. degree from the U.S. Coast Guard Academy in 1961 and a Ph.D. in Metallurgy from the Massachusetts Institute of Technology in 1968. His current professional activities include teaching courses on the fundamental of materials and on corrosion. Additionally he is responsible for a large and active research group studying environmental degradation of materials with particular emphasis on environment mechanical property interactions.

Z.A. POROULIS was trained both in his native Greece and at the Massachusetts Institute of Technology. In addition to post-graduate work at MIT, he has worked on corrosion problems at W.R. Grace and Company and with Exxon Research and Engineering Company.

JEROME KRUGER is in charge of a group concerned with corrosion and electrodeposition at the National Bureau of Standards, having been a member of its staff since 1955. In this capacity he manages a program that encompasses both basic and applied research on a broad range of corrosion areas. Dr. Kruger holds his B.S. (1948) and M.S. (1949) degrees from the Georgia Institute of Technology and a Ph.D. (1952) in Physical Chemistry from the University of Virginia. From 1952 to 1955, Dr. Kruger was with the Naval Research Laboratory where he worked on the mechanism of the action of wash primers and the corrosion products on sacrificial zinc anodes. He has served as chairman of Subcommittee G01.02 and Standing Committee G01.99 as well as the chairman of a number of committees of various corrosion related societies. Dr. Kruger has received both the Silver (1962) and the Gold Metals (1972) of the Department of Commerce. He was the recipient of the Blum Award of the National Capital Section of the Electrochemical Society in 1966, the Willis R. Whitney Award of the National Association of Corrosion Engineers and the Outstanding Achievement Award of the Corrosion Division of the Electrochemical Society in 1977.

STEPHEN R. NOVAK is a Senior Research Engineer in the Materials Technology Division at the U.S. Steel Corporation Research Laboratory in Monroeville, Pennsylvania. He received both a B.S. in 1961 and an M.S. in 1966 from the Mechanical Engineering Department at the University of Pittsburgh, and a Ph.D. in 1977 from the Metallurgical Engineering and Materials Science Department of the University of Pittsburgh. Dr. Novak has been with U.S. Steel for over 20 years and his activities for the last 16 years have concerned various areas of fracture mechanics technology, including those associated with test method development and materials characterization in terms of fracture, fatigue, stress-corrosion cracking, hydrogen embrittlement, and corrosion-fatigue behavior. He has held various technical committee offices in the American Society for Testing and Materials (ASTM) Committee E24 on Fracture, and is also a member of two other ASTM committees, including G1 on Corrosion and E9 on Fatigue. He has also served on various technical committees with other governmental agencies, including the U.S. Navy and the Department of Transportation.